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**THREE-DIMENSIONAL LASER WINDOW FORMATION
FOR INDUSTRIAL APPLICATION**

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ABSTRACT

The NASA Lewis Research Center has developed and implemented a unique process for forming flawless three-dimensional, compound-curvature laser windows to extreme accuracies. These windows represent an integral component of specialized nonintrusive laser data acquisition systems that are used in a variety of compressor and turbine research testing facilities. These windows are molded to the flow surface profile of turbine and compressor casings and are required to withstand extremely high pressures and temperatures. This method of glass formation could also be used to form compound-curvature mirrors that would require little polishing and for a variety of industrial applications, including research view ports for testing devices and view ports for factory machines with compound-curvature casings. Currently, sodium-alumino-silicate glass is recommended for three-dimensional laser windows because of its high strength due to chemical strengthening and its optical clarity. This paper discusses the main aspects of three-dimensional laser window formation. It focuses on the unique methodology and the peculiarities that are associated with the formation of these windows.

INTRODUCTION

An increased interest in fundamental research in turbines and compressors has created a need for nonintrusive optical flow measurement systems. The state-of-the-art systems used in obtaining detailed velocity data are called nonintrusive laser data acquisition systems. These systems seed the airflow with small particles that flow through a fringe pattern which is created by intersecting laser beams. Data are obtained by measuring the pulsating light that is reflected as the seed particles pass through the fringe pattern.

Optically clear laser windows are used so that the laser beams and reflected light can pass through. Normally the laser window glass that is used in wind tunnels is approximately 1.0-in.-thick flat quartz. For turbine and compressor testing facilities, however, the windows are approximately 0.100 in. thick and have three dimensions. The difference between the two windows is shown in figure 1.

Two types of errors can be introduced to the system by the laser window: spatial error of the measurement volume and reduced signal amplitude. Spatial error of the measurement volume is caused when the laser beams pass through the window at incident angles. The actual focal point is then skewed from the desired focal point, resulting in an error [1], as depicted in figure 2. Errors associated with reduced signal amplitude are caused by reflection of the laser beam as it passes through the window. Window size, curvature, thickness, surface quality, and contour tolerance are the major factors that control the magnitude of error.

Because laser windows are molded to the flow surface profile of the turbine and compressor casings, their size and curvature cannot be altered. Window thickness, on the other hand, can vary. Thinner windows are desirable because they minimize error, but the glass must maintain high strength with the reduced thickness. In addition, these thinner curved windows must be able to withstand high pressure and temperature differentials while preserving surface quality. This paper narratively addresses three-dimensional laser window formation and the process that maximizes the surface quality and the contour accuracy. A more detailed explanation of three-dimensional laser window formation is given in [2]. In this paper three-dimensional laser windows will be referred to as "windows."

BACKGROUND

Laser systems are commonly used at NASA Lewis. Most of these systems are located in the engine component test facilities that test compressor and turbine rotors and components. The windows are usually located over rotating hardware where typical instrumentation cannot be used.

Overall safety is of primary concern. Therefore, the windows are hydrostatically pressure tested to 1.5 times the maximum operating pressures of the facilities. Operating pressures for various facilities range between 1.3 and 72 psia. Windows are also thermally qualified at facility temperatures and pressures if thermal differentials are significant. The windows are safety tested on both concave and convex surfaces.

GLASS SELECTION

Several types of glass have been used for window formation at NASA Lewis. Sodium-lime, borosilicate, and sodium-alumino-silicate glasses are among these types. On the basis of the Corning glass code 0317 [2], sodium-alumino-silicate glass has been determined to be the preferred glass for windows. This glass is recommended because of its ultrahigh strength through chemical strengthening, which is unavailable with other glass types. This increased strength allows the use of thinner windows, which reduce spatial error and produce higher quality laser data.

In addition, failure of a chemically strengthened sodium-alumino-silicate laser window will cause the window to shatter in tiny particles, only millimeters in cross-sectional area. This characteristic is advantageous because the smaller particles contain less kinetic energy and are less likely to damage blades or rotors. The particles from other failed glass windows are relatively large in cross-sectional area. A failed chemically strengthened sodium-alumino-silicate window is represented in figure 3.

MOLD DESIGN

The mold material that offers the best results for forming windows is machinable ceramic. The molds for window formation consist of a male and female mold. The male mold is machined to match the internal flow path surfaces, whereas the female mold is machined to these coordinates plus the glass thickness. The overall dimensions of the molds are 1 in. greater than the actual final size of the window glass. Both molds have threaded holes on the perimeter to fit alignment bars.

In order to maintain surface quality, accurate machining and polishing of the molds that are used for window formation are essential. The molds are machined and polished to a tolerance of 0.005 in. of the desired contour with a 16 Ra surface.

All slumping components are machined out of the same material to ensure similar coefficients of thermal expansion. Orientation of the slumping component configuration is shown in figure 4.

GLASS MOLDING

Inert gas furnaces are preferred for slumping because of the heating characteristics of the molds. Other types of furnaces usually introduce contaminants into the slumping environment that degrade glass surface quality. Cleanliness of the molds, glass, and furnace is critical to glass quality. These components should be thoroughly cleaned at the beginning of every slumping operation.

The forming temperature of windows is found by an iterative process. The mean annealing temperature of about 1100 °F is the theoretical starting temperature for new window formation. Adequate visual inspection of the window after slumping will indicate whether the temperature should be increased or decreased. The ideal slumping temperature for three-dimensional window formation is usually within 2 percent of the annealing temperature.

The procedure for window formation is as follows:

- (1) Cut the glass to overall mold dimensions (i.e., 1 in. greater than the final window design dimensions).
- (2) Thoroughly clean the glass with soap and water. Oil from fingers will develop into surface imperfections during the slumping operation.
- (3) Thoroughly clean the male and female molds with an alcohol-based cleaner.
- (4) Thoroughly clean the inert gas furnace.
- (5) Bolt the alignment bars onto the molds.
- (6) Position the male mold into the inert gas furnace.
- (7) Insert the glass on top of the male mold.
- (8) Position the female mold onto the male mold with the glass positioned in between them.
- (9) Heat the furnace to slumping temperature.
- (10) Soak the glass at slumping temperature for 4 to 6 hr.
- (11) Cool the glass down to ambient temperature.
- (12) Examine the slumped glass for proper curvature and quality.
- (13) After desired curvature and quality are obtained, anneal the glass to relieve residual stresses.

Visual inspection of the slumped window will provide adequate information for altering the slumping temperature. If the slumping temperature is excessive, surface imperfections will be apparent. These surface imperfections will appear along the plane of severe three-dimensional contour or at the inflection point. This problem can be solved by decreasing the slumping temperature by 1 to 2 percent of the annealing temperature.

The combination of insufficient slumping temperature and excessive mold pressure may result in low-quality windows. These windows will appear wavy in the area where the glass was stretched. The solution to this problem is to increase both the slumping temperature and duration.

The windows can be molded in several steps by alternating slumping temperatures, modifying slump soak time, varying molding force, inverting mold positions, or any combination of these methods. When molding glass in several steps the female mold is always used first and by itself. After the glass is partially formed, the male mold is added, the entire assembly is inverted, and the slumping process is then repeated. Windows with extreme curvature or compound curvature may require repeated slumping operations. These complex windows often require the addition of weight to the molds to adequately form the glass.

Window development can be a lengthy process, but once the parameters are found for a particular window, reproduction is routine. The last process in the formation of windows is to anneal the glass. Annealing relieves residual stresses that build up in the glass during the development process.

GLASS EDGING

Previous methods of edging the windows to size involved scoring the glass to the desired size, then breaking the glass along this scored edge. During this process, small fragments of glass are broken away along the line of scoring, creating voids in the glass. Minute cracks remain along the edge of the glass after it is broken. These cracks weaken the glass and cause it to fail under load.

Minimizing cracks is important during the edging process. A perfected process for edging glass by using a numerically controlled water-jet cutting machine has been developed and is recommended for cutting windows. The machine abrades glass away along the desired cut line, reducing glass fragmentation. The water-jet cut edge of the glass is less densely populated with cracks, and crack penetration is less severe than with scored glass.

The desired window dimensions are programmed into the numerically controlled water-jet cutting machine. In order to alleviate window glass damage from the backslash of the water jet, a 0.0625-in.-thick aluminum plate is placed across the ways of the water-jet cutting machine bed. In order to protect the glass from fracturing, duct seal is placed over the surface of the aluminum plate to absorb the high cutting frequencies of the

water jet. The window glass is then secured into position by pressing it into the duct seal. This entire assembly is then submersed under water to further assist in absorbing the high cutting frequencies of the water jet. The maximum desired water-jet cutting rate for edging is 4.75 in./min, with a nozzle pressure of 30 000 psig.

After the glass is cut to size, the edges are rounded. Using aluminum oxide sanding belts helps protect the glass from damage because glass edges are most susceptible to impairment. The minimum radius of the rounded edges is equivalent to half the glass thickness, as shown in figure 5.

GLASS STRENGTHENING

Chemical strengthening of the glass through ion exchange is a readily available technology. The process will only be highlighted in this paper; detailed information is given in references 3 to 8.

Windows are chemically strengthened through ion exchange so that they can endure facility operating pressures and temperatures and to increase their relative impact strength. These windows are chemically strengthened to contain a 0.010-in. or greater compression layer. The specially designed chemical composition of Corning glass code 0317 sodium-alumino-silicate glass enhances this ion exchange to ensure maximized glass strength. This is the principal reason why this glass is used for window development.

CONCLUDING REMARKS

High-quality contoured windows are a key part of laser anemometry systems for compressor and turbine facilities. The window development process that was described herein ensures accurate tolerances and flawless quality that could only be previously obtained from grinding and polishing. Although they have been tested for flaws, windows should still be considered and treated as a fragile material. Routine visual inspection and hydrostatic evaluations are considered important to their integrity.

Future experiments will need larger windows to increase the fields of unobstructed view. Future windows must also endure higher pressures and temperature gradients. With the present development processes these windows should successfully withstand these future requirements.

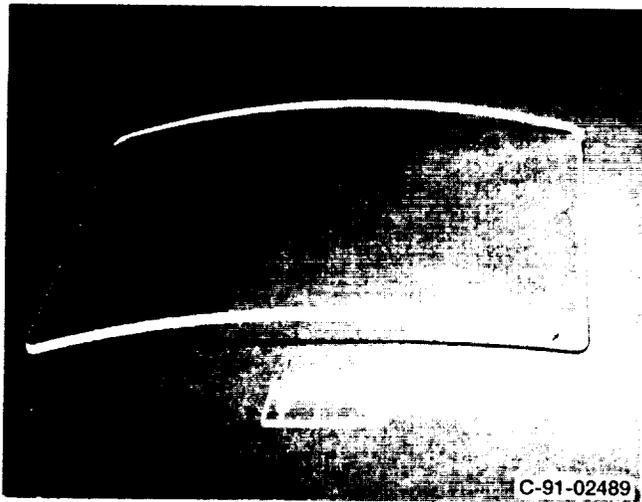
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ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

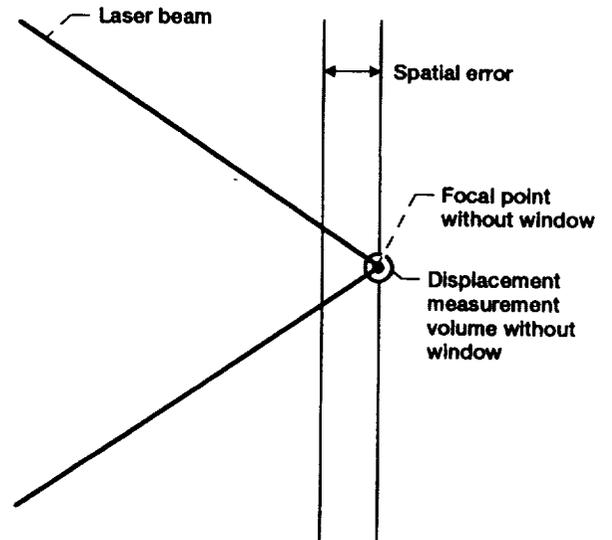


(a) Wind tunnel window.

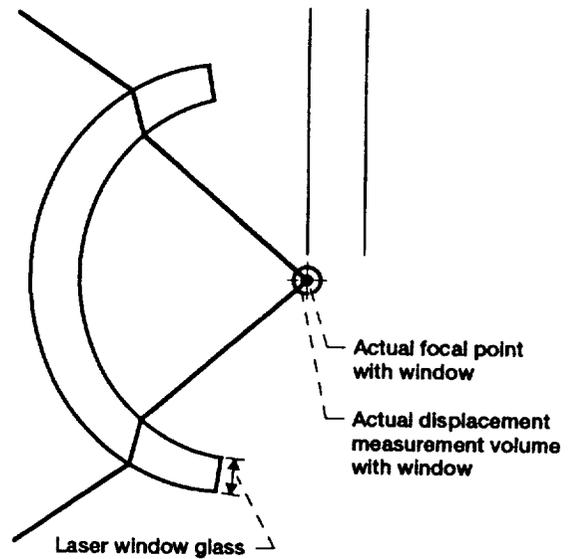


(b) Turbine or compressor window.

Figure 1.—Typical laser windows.



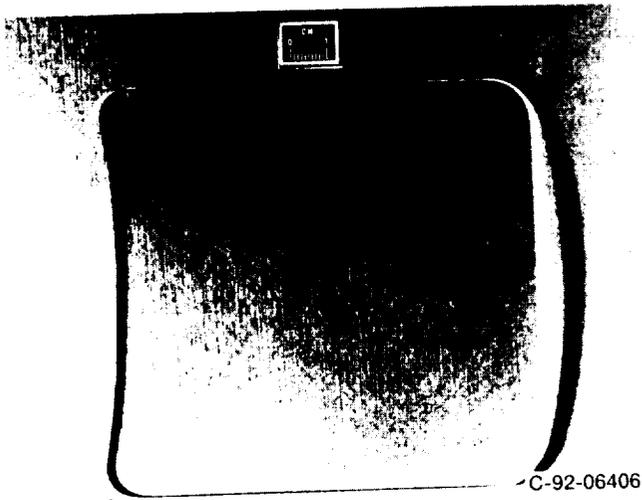
(a) Focal distance without window.



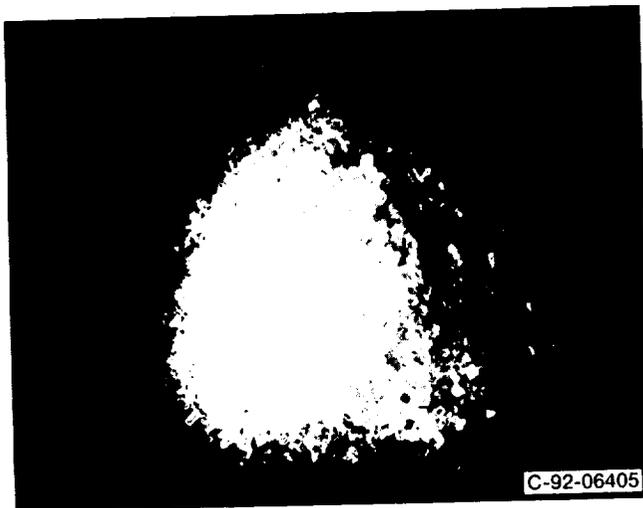
(b) Focal distance with window.

Figure 2.—Spatial error associated with laser windows.

ORIGINAL FACE
BLACK AND WHITE PHOTOGRAPH



(a) Window before failure.



(b) Window after failure.

Figure 3.—Chemically strengthened sodium-alumino-silicate laser window.

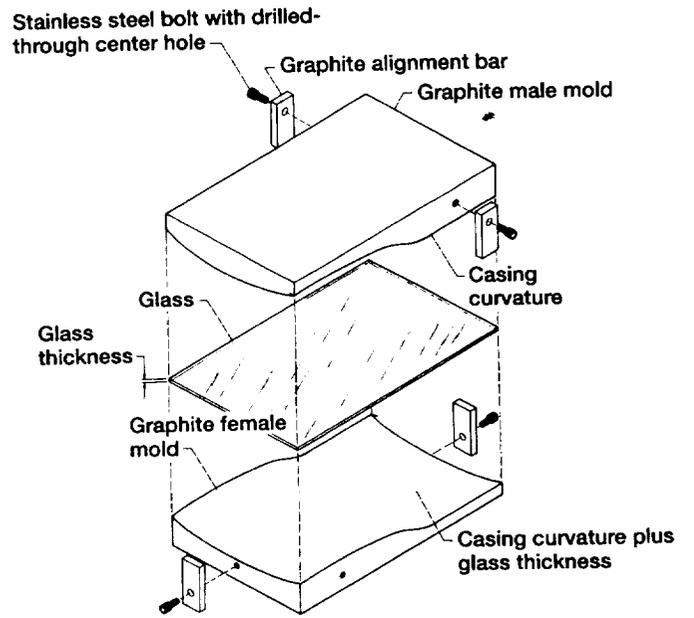


Figure 4.—Slumping components configuration.

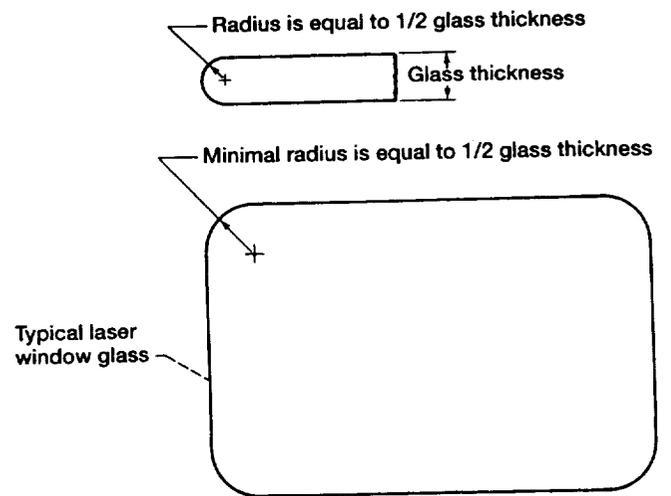


Figure 5.—Rounded edges of typical laser window.